Average over energy effect of parity nonconservation in neutron scattering on heavy nuclei

O. P. Sushkov*
School of Physics, The University of New South Wales, Sydney 2052, Australia

Abstract

Using semiclassical approximation we consider parity nonconservation (PNC) averaged over compound resonances. We demonstrate that the result of the averaging crucially depends on the properties of residual strong nucleon-nucleon interaction. Natural way to elucidate this problem is to investigate experimentally PNC spin rotation with nonmonachromatic neutron beam: $E \sim \Delta E \sim 1 MeV$. Value of the effect can reach $\psi \sim 10^{-5} - 10^{-4}$ per mean free path.

Enhancement of parity nonconservation (PNC) in neutron scattering near compound resonances was predicted in 1980 [1] and first observed experimentally in Dubna in 1981 [2] for lowest p-wave resonance in ^{117}Sn. During next decade the effect was observed in several more resonances in different nuclei. The magnitudes of the effect were in brilliant agreement with statistical theory [1] (for review of theory see articles [3,4]). New development arose in 1990-1991 with appearance of Los Alamos data for ^{238}U [5] and especially for ^{232}Th [6] (also see paper [7]). Number of resonances where the effect was observed became big, and it was clear that average value of the effect was not equal to zero, contrary to the expectation of the statistical theory. There have been several theoretical works devoted to this problem (for a review see Ref. [4]), but situation remains unclear.

Let us first consider possible scenarios for for the resolution of the problem. 1) Nonzero average is just a statistical fluctuation, because number of resonances where the effect has been observed is still not very big. 2) There is some gross structure in the effect: nonzero average over interval ϵ which is much bigger than distance between resonances and much smaller than 1 MeV ($D \ll \epsilon \ll \Delta E \sim 1MeV$). But the average over interval $\Delta E \sim 1MeV$ is still zero or at least very small. 3) Nonzero average over $\Delta E \sim 1MeV$.

First possibility can not be ruled out, but even if present value is a fluctuation there is a question about expected average value. Existence of gross structure would mean that there are some intermediate states of opposite parity separated by the interval ϵ. This relatively small interval can work only if it is bigger than the width of corresponding states. However the spread widths of any known intermediate state $\Gamma_{spr} \sim 1MeV$, and this probably kills the gross structure scenario. In the present work we consider third scenario: Nonzero average over interval $\Delta E \sim \Gamma_{spr} \sim 1MeV$. It will be important for us that only elastic channel is open [(n, γ) can be neglected anyway] . This is why ΔE should not be bigger than 1 MeV.

Thus let us consider scattering of a neutron with energy $E \sim \Delta E \sim 1MeV$. Certainly at this energy there is no kinematic enhancement of PNC effect because $kR \sim 1$ ($k = \sqrt{2mE}$ and R is radius of the nucleus). But this is irrelevant to the problem of averaging because the kinematic enhancement at small energy is due just to trivial suppression of an incident neutron wave function by centrifugal barrier.

At $E \sim 1MeV$ the width of each particular compound resonance Γ_c is of the order of distance between the resonances $\Gamma_r \sim D$. Therefore an averaging over the resonances is equivalent to the averaging over continuous energy. Due to Heisenberg uncertainty relation $\Delta E \cdot \Delta t \sim 1$ we can replace the averaging over energy interval ΔE by consideration of a wave packet localized in time with uncertainty $\Delta t \sim 1/MeV$. This is equivalent to semiclassical approximation. Certainly at $E \sim \Delta E \sim 1MeV$ semiclassical parameter is not very good: $2R/v\Delta t \sim kR \sim 1$, but still it is reasonable. So instead of energy representation we intend to consider space-time picture of the scattering.

An effective Hamiltonian of a nucleon weak interaction with nucleus is of the form

$$H_W = g_a \frac{G}{2\sqrt{2}m}\{\sigma\mathbf{p}, \rho(r)\} \approx g_a \frac{G\rho}{\sqrt{2}m}\sigma\mathbf{p}. \tag{1}$$

Here $G \approx 10^{-5}/m^2$ is Fermi constant, $m, \mathbf{p}, \sigma$ - mass, momentum and spin of the nucleon. ρ is nuclear density ($\int \rho dV = A$) which is taken to be constant. g_a is effective constant of the weak interaction: $|g_n| < 1$, $g_p \approx 5$ (see e.g. Refs. [8,9]).

Let us first consider "direct" or "potential" process when neutron passes nucleus without excitation of other nucleons. Angle of the neutron spin rotation is equal to the phase difference between positive and negative helicity neutrons

$$\psi = p_+ d - p_- d = \left(\sqrt{2m(U + W_n)} - \sqrt{2m(U - W_n)}\right) d \tag{2}$$

Here $U \approx 40 MeV$ is value of the nuclear potential, and $W_n = g_n G\rho p/\sqrt{2}m = g_n G\rho\sqrt{U/m}$ is weak interaction. Assuming that $d \sim R = r_0 A^{1/3}$ we find from (2)

$$\psi \sim \sqrt{2} g_n R G \rho = g_n \frac{3}{2\sqrt{2}\pi} 10^{-5} \frac{A^{1/3}}{m^2 r_0^2} \approx g_n 10^{-6}. \tag{3}$$

Per mean free pass each neutron passes in average one nucleus. It means that above estimation corresponds to the neutron mean free path.

During passage of nucleus the neutron can excite other nucleons and hence produce the cascade. Probability of this process is about 1, because at spread width $\Gamma_{spr} \sim 3MeV$ mean free path of a neutron in nuclear matter is of the order of nuclear size: $l/2R \sim \sqrt{2U/m}/2\Gamma_{spr} R \approx 1.5$ The nucleons excited in the cascade can not get out of nucleus because energy of each particular nucleons is not enough to escape. So nucleons are trapped. If nucleus would be an infinite system the cascade would never inverted due to second law of thermodynamics. However nucleus is finite with finite density of spectrum, therefore the cascade is inverted after quantum time $\tau \sim 1/D$, and neutron escapes. Ratio of the neutron life time in this quantum trap to the time of free pass is

$$N = \frac{v}{2DR} = \frac{\sqrt{2U/m}}{2Dr_0 A^{1/3}} \sim \frac{5MeV}{D} \sim 10^6. \tag{4}$$

This is exactly the parameter which involves in the compound resonance theory [1].

Life time in the trap can enter into some physical effects. For example let us imaging some magnetic field inside nucleus and assume that nuclear forces are spin independent. Then Faraday rotation of the spin of the trapped neutron is $\mu_n \mathcal{H} \tau$, and this is by N times bigger than the Faraday rotation in the "potential" process. (One can easily come to the same conclusion using perturbation theory and compound-resonance representation).

We are interested in the weak interaction (1) which is proportional to $\sigma\mathbf{p}$. Let us assume first that nuclear forces (residual interaction, as well as selfconsistent potential) are spin independent. In this situation spin is separated from orbital motion, and average value of the momentum p in cascade corresponds to free passage. However, due to the charge exchange forces, the cascade protons also contribute into spin rotation, and estimation (3) should be replaced by

$$\psi \sim g_p 10^{-6} \sim 0.5 10^{-5}. \tag{5}$$

Let us assume now that helicity of the particle is conserved in the nuclear scattering. The examples of such conservation are well known. It is enough to recall that in quantum electrodynamics at high energy scattering the helicity of an electron is conserved. With

the assumption about helicity conservation we come to the estimation of the neutron spin rotation $\psi \sim N g_p 10^{-6} \sim g_p$. It certainly is not realistic. Helicity in the cascade is not conserved exactly. Let us denote by τ_m the time of memory about initial helicity. Then we get the following estimation of the angle of neutron spin rotation.

$$\psi \sim \frac{\tau_m}{\tau_f} g_p 10^{-6}. \tag{6}$$

Here $\tau_f \sim 2R/v$ is the time of free passage of nucleus. To fit experimental data we need $\tau_m/\tau_f \sim 10$ (One should not forget about kinematic enhancement $\sim 1/kR \sim 5 \cdot 10^2$ for low energy data [5–7]). We would like to note that the considered picture is somewhat similar to the "quasielastic mechanism" suggested in Ref. [10] (see also Ref. [11]). However it is probably impossible to derive semiclassical result basing on perturbation theory used in Refs. [10,11].

After first step of the cascade we have three quasiparticles in the system. So each quasiparticle has in average 1/3 of the initial excitation energy. According to standard Landau estimation, the spread width of quiasiparticle is proportional to $\propto E^2$. Therefore $\Gamma'_{spr} \sim (1/3)^2 \Gamma_{spr} \sim 0.3 MeV$. It means that each of these quasiparticles lives long enough before decay into more complicated configurations, and in first approximation we can forget about this decay (cf. with Ref. [11]), but basically it should be included as well. To avoid misunderstanding we stress that Γ'_{spr} is the spread width of qusiparticle. The spread width of configuration is 3 times bigger. There is a bunch of classical trajectories in nuclear potential along which the helicity is conserved. However to simulate the cascade one needs also to know the spin-isospin structure of the residual strong interaction. Unfortunately, existing parametrizations [12] are not very reliable. Nevertheless one can try to do Monte Carlo simulations of the cascade. We can move in opposite direction and consider the experimental data [5–7] as a direct measurement of the memory time: $\tau_m/\tau_f \sim 10$. In this case we can expect the angle of neutron spin rotation per mean free pass of nonmonochromatic beam ($\Delta E \sim 1 MeV$) to be $\psi \sim 10^{-4}$. The discussed effect is independent of nucleus and in this sense it is regular, but still it is related to the complex structure of the cascade and sign of the effect is not obvious.

In the present paper we have considered semiclassical picture of the neutron spin rotation caused by parity nonconserving weak interaction. We demonstrated that the calculation can be reduced to Monte Carlo simulation of the cascade which is much simpler than an exact quantum calculation for compound states. The semiclassical picture is equivalent to the averaging of the effect over energy interval $\Delta E \sim 1 MeV$. This can be investigated experimentally with nonmonochromatic neutron beam. We demonstrated that the angle of rotation can reach $\psi \sim 10^{-5} - 10^{-4}$ per mean free path. The upper estimation ($\psi \sim 10^{-4}$) is based on experimental data [5–7] when we treat them as a measurement of τ_m.

I am very grateful to V. V. Flambaum, G. F. Gribakin and D. L. Shepelyansky for discussions. This work has been completed during my stay at the Laboratoire de Physique Quantique, Universite Paul Sabatier. I am gratefully acknowledge the hospitality and financial support.

REFERENCES

* Also at the Budker Institute of Nuclear Physics, 630090 Novosibirsk, Russia.

[1] O. P. Sushkov and V. V. Flambaum, Pis'ma Zh. Eksp. Teor. Fiz., **32**, 377 (1980) [JETP Lett., **32**, 363 (1980)].

[2] V. P. Alfimenkov et al, Pis'ma Zh. Eksp. Teor. Fiz., **34**, 308 (1981) [JETP Lett., **34**, 295 (1981)].

[3] O. P. Sushkov and V. V. Flambaum, Usp. Fiz. Nauk, **136**, 3 (1982) [Sov. Phys. Usp., **25**, 1 (1982)].

[4] V. V. Flambaum and G. F. Gribakin, Prog. Part. Nucl. Phys., **35**, 423 (1995).

[5] J. D. Bowman et al, Phys. Rev. Lett., **65**, 1192 (1990).

[6] C. M. Frankle et al, Phys. Rev. Lett., **67**, 564 (1991).

[7] C. M. Frankle et al, Phys. Rev., C **46**, 778 (1992).

[8] V. V. Flambaum, I. B. Khriplovich and O. P . Sushkov, Phys. Lett., B **146**, 367 (1984).

[9] O. P. Sushkov and V. B. Telitsin, Phys. Rev. C **48**, 1069 (1993).

[10] V. V. Flambaum, Phys. Rev., C **45**, 437 (1992).

[11] M. S. Hussein, A. K. Kerman and C-Y Lin, Z. Phys. A **351**, 301 (1995).

[12] A. B. Migdal, Theory of Finite Fermi Systems and Applications to Atomic Nuclei. John Wiley & Sons, New York, 1967. G. E. Brown, Rev. Mod. Phys., **43** 1 (1971). V. A. Khodel and E. E. Saperstein, Phys. Rep., **92**, 183 (1982).